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(54) Title: APPARATUS FOR ACOUSTIC DETECTION OF PARTICLES IN A FLOW USING A FIBRE OPTIC INTERFEROMETER
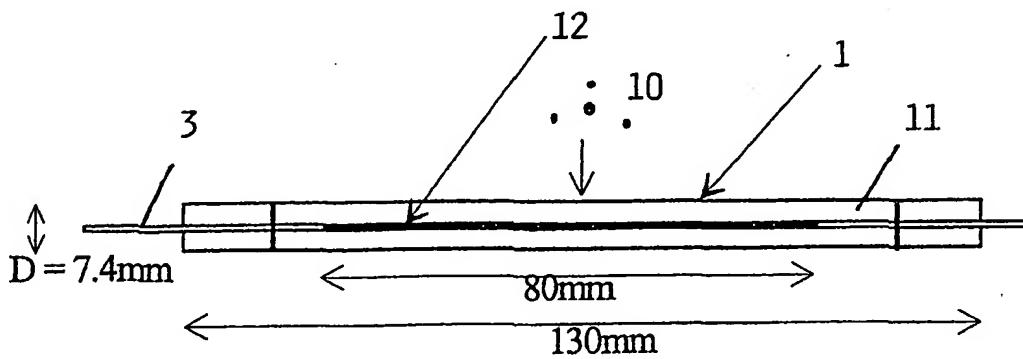
(57) Abstract: Fibre optic particle detector for measurements in a fluid flow, comprising an optical fibre being acoustically coupled to a mechanical element adapted to be acoustically coupled to the flow, a fibre optic interferometer and a light source providing light in said optical fibre.

Apparatus for acoustic detection of particles in a flow using a fibre optic interferometer

This invention relates to an apparatus for detection of particles in a liquid/gas flow using a fibre optic interferometer.

5 Background

Sand production in oil and gas wells is a serious problem mainly due to sand induced erosion. It is therefore of great interest to accurately detect the presence of sand and the amount of produced sand to maximise the oil/gas
10 production rate and still maintain sand-free production.

Sand can be measured either with intrusive sensors, i.e. obstructions in the oil/gas flow, or with non-intrusive sensors. Intrusive sensors can either be based on measuring the erosion of the obstruction/probe, or on measuring the
15 acoustic emission generated when the particles hit the obstruction. Conventional non-intrusive sensors are based on ultrazonic (PZT) transducers mounted at bends in the pipe, where particles will impact the inside of the pipe wall, generating an ultrasonic pulse which is picked up by the
20 acoustic sensor. Non-intrusive sensors are much preferred unless intrusive sensors can offer significantly better performance. However, non-intrusive sensors will require bends, and is believed to be less sensitive than intrusive sensors.

25   Acoustic sensors should be able to measure acoustic signals at frequencies > 100kHz, or ideally >500kHz, where sand noise is dominant over other noise sources, to provide unambiguous sand monitoring with high signal-to-noise ratio. Other noise sources include flow generated noise,
30 mechanical/structural noise and noise from electrical equipment (eg. from electrical submersible pumps). Provided the individual hits can be separated in time, the quantity of produced sand can be derived from the number of hits and the signal amplitudes resulting from each hit. To be able to
35 reliably detect sand particles and verify sand-free production with acoustic sensors, extreme sensitivity with large signal-to-noise ratio is required. Sand particles of interest have diameters ranging from 50-400mm.

Fibre optic interferometric sensors are known to offer high sensitivity and resolution for dynamic measurands, which make them particularly attractive for acoustic sensing, eg. as hydrophones, see for example [T. G.
5   Giallorenzi et.al., "Optical fiber sensor technology," IEEE J. Quantum Electron., Vol. 18, pp. 626-665, 1982]). The small dimensions of an optical fibre provides the potential for high frequency acoustic sensing, and the use of fibre optic interferometric sensors for ultrasonic acoustic
10   sensing has been investigated [N. Lagaros et.al. "Ultrasonic acoustic sensing," Proc. SPIE, Vol. 798, pp. 94-101, 1987], [D. Wiesler et.al., "Fiber optic ultrasound sensors for medical imaging applications", 12th Intern. Conf. on Optical Fiber Sensors, Willamsburg, USA, pp. 358-361, 1997.]. A
15   fibre optic interferometric sensor typically consists of two optical paths, where the optical path length difference is modulated by the measurand. The interferometer is normally excited by a laser source and the changes in differential optical path length is causing a modulation of the light
20   intensity at the output of the interferometer. It is known that the sensitivity and resolution is improved by using a high coherence laser source.

One known high coherence laser source is the fibre distributed feedback (DFB) laser [US patent 5,771,251 to J.
25   T. Kringlebotn et.al.], which consists of a single fibre Bragg grating providing feedback in a gain fibre, typically an erbium-doped fibre pumped by a semiconductor laser. Such as laser typically has a coherence length of several kilometres. It is further known that such a laser also can
30   be used as a sensor element [US patent 5,844,927 to J. T. Kringlebotn], for example for acoustic sensing, where the acoustic field modulates the stresses in the fibre laser and hence the optical frequency of the fibre laser, which can be measured using an optical interferometer which converts the
35   frequency fluctuation into intensity fluctuations. The low coherence length of the laser allows the use of large path length imbalance in the interferometer and hence a high sensitivity. It is known that several fibre DFB lasers can be wavelength multiplexed along one optical fibre. Finally,

is also known that several interferometric sensors can be multiplexed along one or several optical fibres, for example by using Fabry-Perot type interferometers based on pairs of low-reflectivity FBG reflectors, where each pair has a
5　different Bragg wavelength.

Fibre optic sensors are passive, with no electrical parts/wiring, and can provide reliable operation at high temperatures up to at least 200°C. The large bandwidth of an optical fibre also means that an almost unlimited amount of
10　high frequency raw data can be transmitted along the fibre.

Interferometric techniques combined with high coherent sources allow highly sensitive dynamic measurements with low noise, hence providing good signal-to-noise ratio measurements. The potentially small dimension of these fibre
15　optic sensors, in particular the DFB fibre laser sensor, allows for high frequency acoustic sensing [D. Thingbø, E. Rønnekleiv, and J. T. Kringlebotn, "Intrinsic distributed feedback fibre laser high-frequency hydrophone," Techn. Dig., Conf. on Bragg gratings, Photosensitivity, and Poling
20　in Glass Waveguides, " pp. 57-59, Florida, US, Sept. 23-25, 1999].

Objective

The main objective of the present invention is to provide a reliable method and apparatus for high resolution
25　detection of particles present in a liquid and/or gas flow in harsh environments with high temperature and/or pressure, such as encountered down-hole in an oil and gas well.

In particular the objective is to provide a reliable method and apparatus for permanent downhole detection of
30　sand particles to determine the amount of produced sand from oil and gas wells to maximise the oil/gas production rate and still maintain sand-free production.

A further objective is to provide a method and apparatus for multi-point/distributed particle detection,
35　which is very attractive for permanent downhole multi-zone sensing of sand production in a multi-zone well.

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Invention

The objectives states above is obtained using a
particle detector characterized as stated in the independent
claim. The main part of the invention comprises the use of
5 at least one optical fibre attached to or embedded in a
mechanical transducer element where particles hitting this
element or a mechanical structure in physical contact with
the transducer element generate high frequency acoustic
waves causing a modulation of the stresses, and hence the
10 optical path length and/or the birefringence in the optical
fibre attached to the transducer element.

The transducer element can be hit directly by the
particles to be detected, which will be the case if the
element is an intrusive element placed fully or partly
15 inside a pipe where the flow contains the particles to be
detected. Alternatively the transducer element can be non-
intrusive by clamping it to a mechanical structure, for
example at a bend of a pipe, where the particles in the flow
inside the pipe will hit the pipe wall generating acoustic
20 waves which are picked up by the transducer element.

In the following the invention will be described with
reference to the accompanying drawings, illustrating the
invention by way of examples.

Figs. 1A-C   illustrate three different embodiments of the
25   invention being adapted for intrusive or non-
                intrusive coupling to the flow.

Fig. 2A-C   illustrates the positioning of the three
                embodiments of the invention in or on a pipe.

Figs. 3A-C   illustrates alternative optical fibre systems
30   for detecting the vibrations generated by the
                particles in the flow.

Figs 4A-C   illustrating examples of measurements using
                the embodiment according to fig. 1C.

Figs 5A-B   illustrating examples of measurements using
35   the embodiment according to fig. 1B.

Figs 6A-B   illustrating examples of measurements using
                the embodiment according to fig. 1A.

Fig. 1 shows a schematic illustration of basic
experimental transducer designs:

a) Intrusive fibre laser sensor transducer, using a fibre
    DFB laser 12, where the laser fibre is placed in a hole
    at the centre of a 13cm long steel rod 11 having a
    diameter of 7mm, and the hole is filled with silicon
5   oil. The probe 1 is made to go through a flow pipe at
    90°, as illustrated in Fig. 2A, with the centre of the
    laser at the centre of the pipe, such that the sand
    particles hit the probe at 90°. The particles 10
    hitting the probe wall will set up ultrasonic waves in
10 the probe modulating the stresses in the fibre laser
    and hence the laser frequency.

b) Intrusive interferometric sensor transducer, consisting
    of a 10cm long solid steel cylinder 13 having a
    diameter of 12mm, with a sensing fibre 2 coiled around
15 the cylinder 13 inside a 1mm deep square groove 15 with
    a width t = 3-6mm, positioned at a distance Δ = 2-5mm
    from the end surface. The probe 1 is inserted into the
    flow through the pipe wall at an angle of 45°, as
    illustrated in Fig. 2B, with the fibre coil end outside
20 the pipe wall. The intrusive probe in is based on
    acoustic wave pulse propagation along the cylindrical
    steel excited by sand particles hitting the end of the
    probe which is inside the pipe. The probe will
    theoretically be a single mode acoustic waveguide for
25 acoustic frequencies f_c < V_T/D, where V_T is the sound
    shear velocity in the material, which for steel is ca.
    3200m/s, implying that f_c (for a cylinder diameter of D
    = 12mm) is ca. 270kHz. The propagation pressure waves
    inside the waveguide will induce some radial expansion
30 of the cylinder. This will cause a strain modulation of
    the fibre coil, which can be measured optically. Due to
    interference between the forward and backward
    propagating waves at the end of the probe there will be
    a resonance when the distance from the end face to the
35 centre of the fibre coil equals a quarter of the
    acoustic wavelength λ_a, i.e. when λ_a/4 = Δ+t/2.

c) Non-intrusive interferometric sensor transducer
    consisting of a cylinder 14 with a fibre coil 2 wrapped
    around the cylinder inside a groove 15. The material of

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the fibre coil section is Torlon, which is a plastic
material chosen to enhance the radial expansion due to
the acoustic pressure wave. Other materials can be
used, including steel. The transducer is clamped at the
5   outside of a flow pipe near a bend, as illustrated in
Fig. 2. The inner section is slightly curved to give
better contact with the pipe, and a gel is used to
improve the acoustic transfer of energy. The groove
cylinder is made of Torlon, which is plastic material
10   chosen to enhance the radial expansion due to the
acoustic pressure wave. The outer section is made of
steel and has a thickness Δ = 6mm.
       Fig. 2A-C illustrate the positioning of the three
embodiments of the invention in or on a pipe. The
15   embodiments can be used in a low pressure, low temperature
test water flow loop. More complex embodiments have to be
used in a real high temperature, high pressure oil and gas
well, using high pressure seals and high temperature
materials.
20   Fig. 2A illustrates the positioning of the intrusive
fibre laser sensor transducer 11,12 shown in Fig. 1A in a
pipe 21 with a water and sand flow. O-rings 22 are placed
between the pipe and the transducer house 23 as pressure
seals to prevent the water to penetrate out of the pipe and
25   also for acoustic damping. In a real high pressure oil-well
applications high-pressure-seals are required. O-rings 24
are also used between the transducer house and the steel
transducer 11 containing the fibre laser 12 to acoustically
decouple the transducer from the housing and the pipe. In
30   this case the fibre is terminated inside the transducer, but
a pass-through device with access to both ends of the fibre
laser, which is necessary for multiplexing of several
sensors along one fibre can be realised.
       Fig. 2B illustrates the positioning of the intrusive
35   interferometric sensor transducer 2,13 shown in Fig. 1B in a
pipe 37 with a water and sand flow in the direction of the
arrow. The transducer 2,13 is placed at an angle of 45° to
the flow direction. The optical fibre coil 2 is positioned
outside the pipe. As in Fig. 2A the transducer is separated

from the housing 33 with O-rings 35. The housing is
separated from the transverse pipe section 34 with other O-
rings 36.

Fig. 2C illustrates the positioning of the non-
5   intrusive interferometric sensor transducer shown in Fig.
1C. The transducer 2,14,43 is clamped with an elastic rubber
band 41 to the pipe wall 45 in a bend of a flow loop with
the water and sand flowing in the direction of the arrow.
The transducer consists of a plastic cap 43 outside a steel
10   section 14 with the fibre 2 wrapped around it in a groove.
The material of the fibre coil section is Torlon, which is a
plastic material chosen to enhance the radial expansion due
to the acoustic pressure wave. Other materials can be used,
including steel.

15   Fig. 3A-C shows a schematic illustration of the optical
sensor system using a fibre optic interferometer in
combination with a highly coherent fibre distributed
feedback (DFB) lasers, where the laser is either used as the
sensing elements with interferometric readout (Fig. 3A), or
20   as a source for reading out an interferometric fibre coil
sensors, as illustrated in Fig. 3B and 3C.

As illustrated in fig. 3A the optical fibre 3 can be an
active fibre laser or partially be such a laser, typically a
fibre DFB laser 55, where a change in optical path length
25   will cause a modulation of the laser frequency, which can be
converted to a detectable intensity modulation by a
receiving interferometer, in this example comprising a pump
laser 51, a connector 52, a detector 53 as well as a well
known fibre interferometer 54, e.g. a Michelson
30   interferometer, with a PZT phase modulator 57 and a fibre
coil 58. A change in birefringence can be detected by
measuring the beat frequency between the two orthogonally
polarised laser frequencies of a dual-polarisation fibre DFB
laser 55.

35   Alternatively the optical fibre 3 in the sensor can be
part of an optical interferometer 54, as illustrated in
figure 3B, where a change in optical path length and/or
birefringence in the fibre coil 2 can cause a modulation of
the light intensity at the output of the interferometer 54

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when the interferometer is illuminated by a light source
51,55, typically a high coherence laser such as a fibre DFB
laser. Typically the optical fibre 3 will be fibre coil 2
wrapped around the transducer element.

5   Alternatively the interferometer in the optical fibre 3
in the sensor can be a passive fibre Bragg grating (FBG) or
part of such a grating, as illustrated in fig. 3C, where a
change in optical path length and/or birefringence can cause
a modulation of the light intensity of the reflected light
10 from the grating 56 when the grating is illuminated by a
light source 51, 55, typically a high coherence laser such
as a fibre DFB laser 55. The grating can include a phase-
shift that provides a sharp dip in the reflection spectrum.
When the laser wavelength is positioned at the steep edge of
15 this dip the magnitude of the modulated reflected light
intensity will be greatly enhanced, hence enhancing the
resolution.

       Several fibre optic sensor elements, either
interferometric sensors, laser sensors, or FBG sensors
20 attached to or embedded in separate mechanical transducer
elements, can be multiplexed along one optical fibre. The
readout instrumentation and signal processing can be placed
several kilometres from the sensor elements linked by a
single optical fibre.

25   Fig. 4A shows the measured signal time response of the
non-intrusive fibre interferometric sensor transducer shown
in Fig. 1C when a single sand particle is hitting the inside
of the steel bend. The corresponding PZT transducer signal
is shown for comparison. We see that the signals are quite
30 similar, as are also the signal-to-noise ratios. Fig. 4B and
4C shows the corresponding frequency spectra and also the
spectra with a sand-free flow. For both the PZT and the
fibre optic probe the signals are strongest between 100 and
300kHz, related to mechanical resonances in the pipe wall,
35 and also the angle and position of the sand particle hit. At
these high frequencies the sand induced signals will
dominate over other noise sources to provide a good signal-
to-noise ratio.

Fig. 5A shows the measured signal time response with the intrusive fibre interferometric sensor transducer shown in Fig. 1B. Fig. 5B shows the corresponding frequency spectrum with maxima in the frequency range of 250-300kHz. The

5 expected resonance frequency as discussed under Fig. 1 is ca. 310kHz.

Fig. 6A and 6B show the time response and corresponding frequency response of the intrusive fibre laser probe shown in Fig. 1A. From the time response in Fig. 6A the signal-to-

10 noise ratio is seen to be very high. The main resonance is around 80kHz.

C l a i m s

1. Fibre optic particle detector for measurements in a
fluid flow, comprising an optical fibre, an optical
interferometer, an optical light source providing light in
said fiber, the optical fiber being attached to or embedded
in a transducer element,
c h a r a c t e r i z e d in that the transducer element or
a mechanical structure which is in acoustic contact with the
transducer element is arranged to be hit by particles moving
in the flow by exposing part of said transducer element or
said mechanical element to the flowing fluid, each particle
hitting the exposed part thus generating acoustic waves
propagating some distance in the mechanical structure and/or
transducer element to the optical fibre.

2. Particle detector according to claim 1, wherein at
least a part of the mechanical element has a circular cross
section around which the optic fibre is coiled.

3. Particle detector according to claim 1, wherein the
circular part of the mechanical element is a groove.

4. Particle detector according to claim 1, wherein the
mechanical element constitutes rod having a longitudinal
hole, the optical fibre being positioned in said hole.

5. Particle detector according to claim 1, wherein the
light source is constituted by the optical fibre at least
partially constituting an active fibre laser, typically a
fibre DFB laser.

6. Particle detector according to claim 1, wherein the
light source is a high coherence laser, e.g. a fibre DFB
laser.

7. Particle detector according to claim 1, wherein the
optical fibre is part of an optical interferometer in which

a change in optical path length and/or birefringence
resulting from the coupled acoustic vibrations cause
modulations of the light intensity at the output of the
interferometer.

8.　Particle detector according to claim 1, wherein the
optical fibre comprises at least part of a passive fibre
Bragg grating (FBG), and a light source coupled to the
optical fibre, illuminating said grating.

9.　Particle detector according to claim 8, wherein said
grating includes a phase-shift providing a sharp dip in the
reflection spectrum. When the laser wavelength is positioned
at the steep edge of this dip the magnitude of the modulated
reflected light intensity will be greatly enhanced, hence
enhancing the resolution.

10.　Particle detector according to claim 1, comprising
several fibre optic sensor elements, either interferometric
sensors, laser sensors, or FBG sensors coupled to separate
mechanical transducer elements.
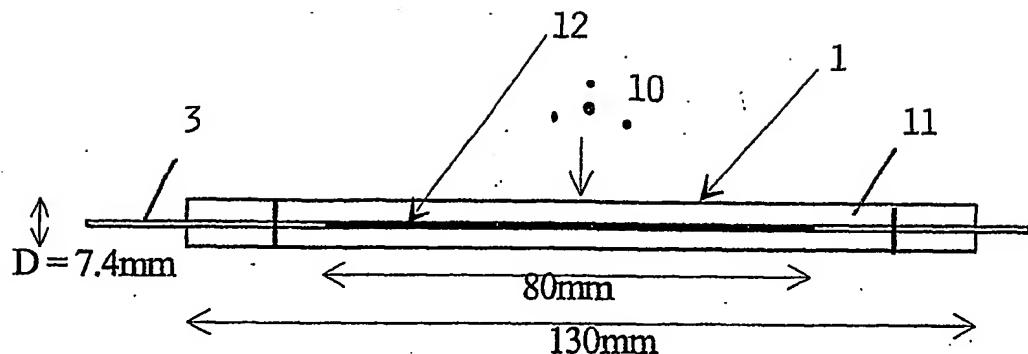
FI G. 1A
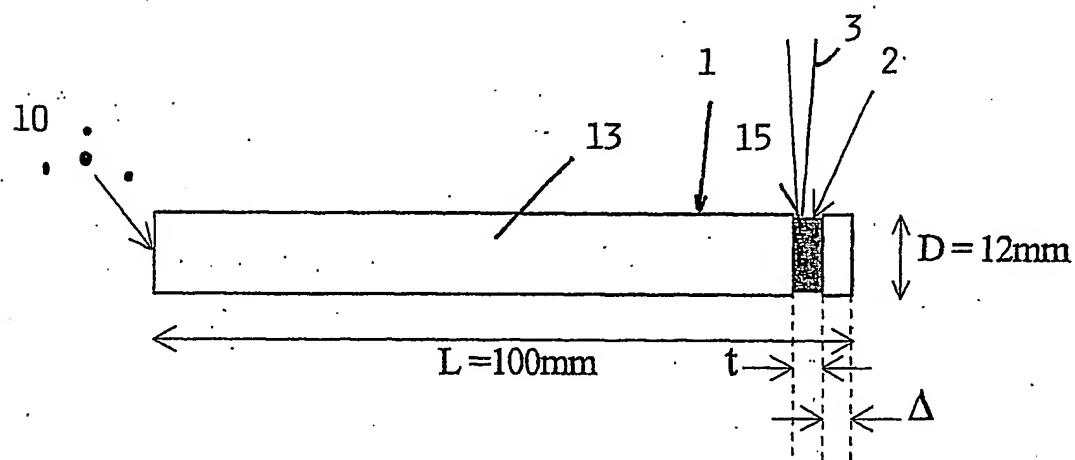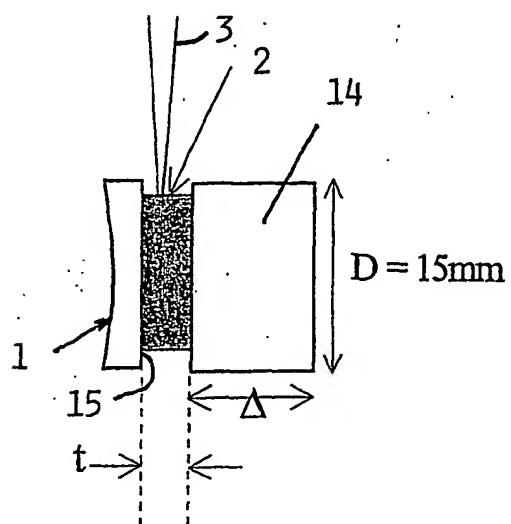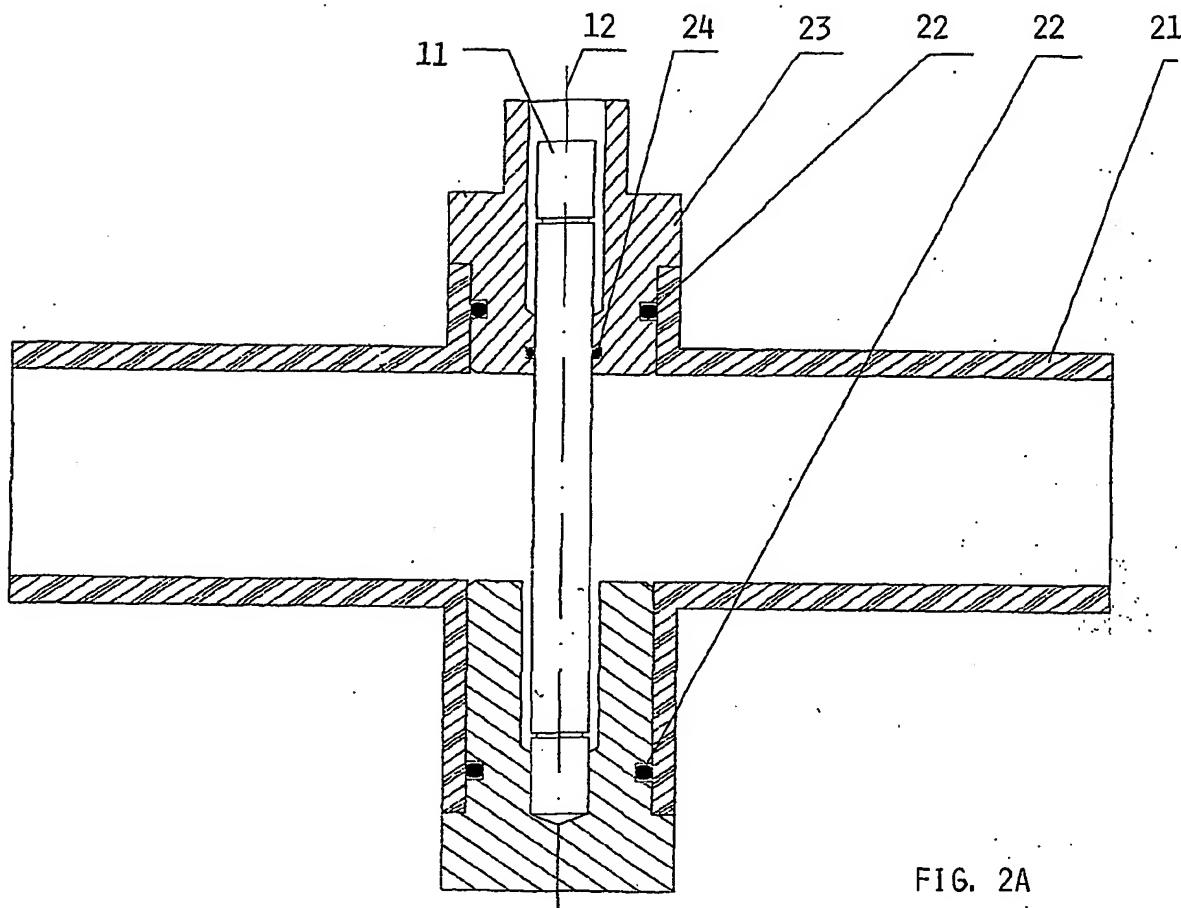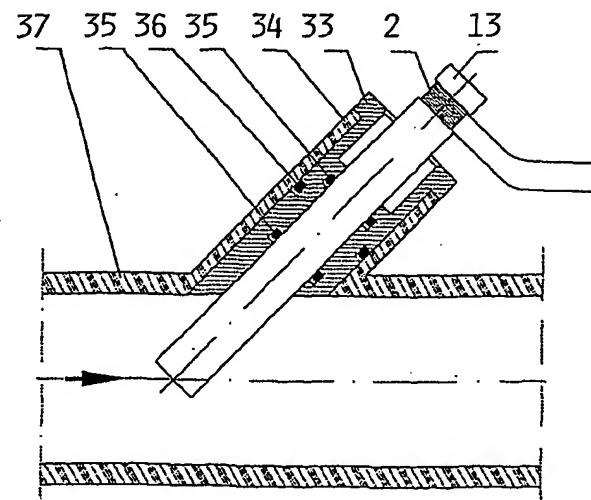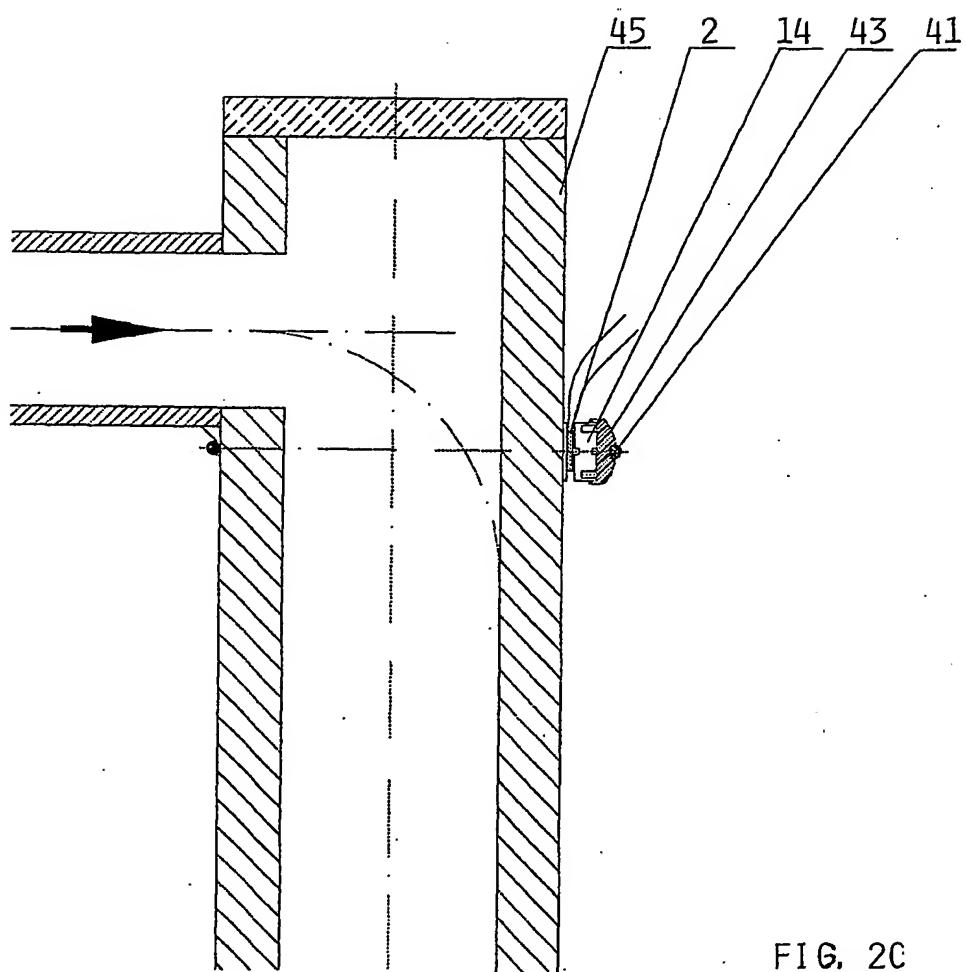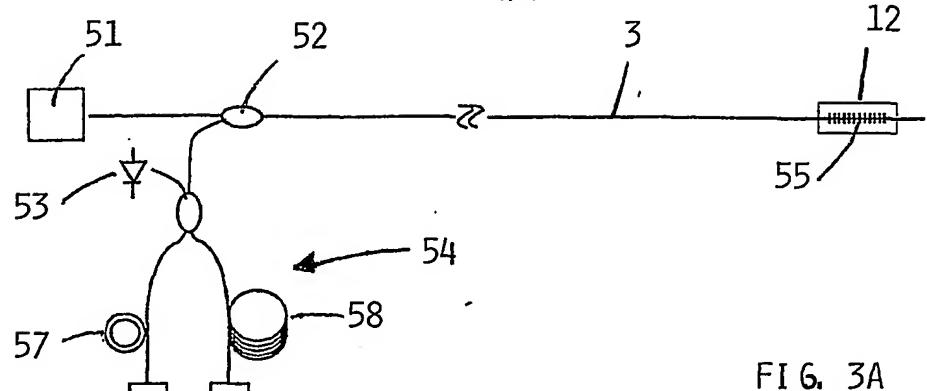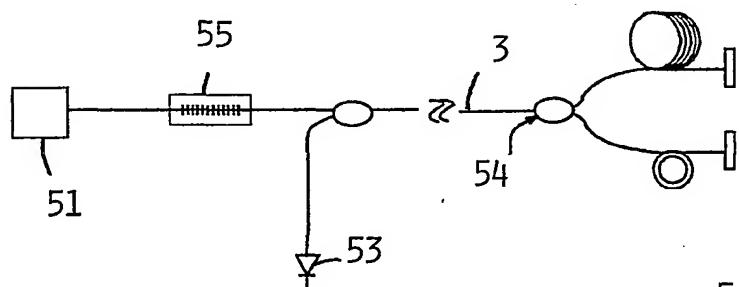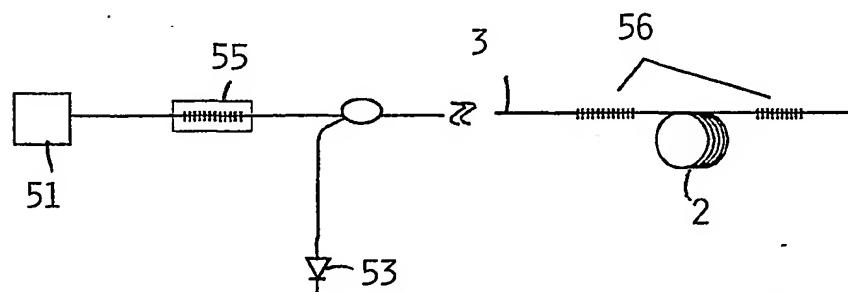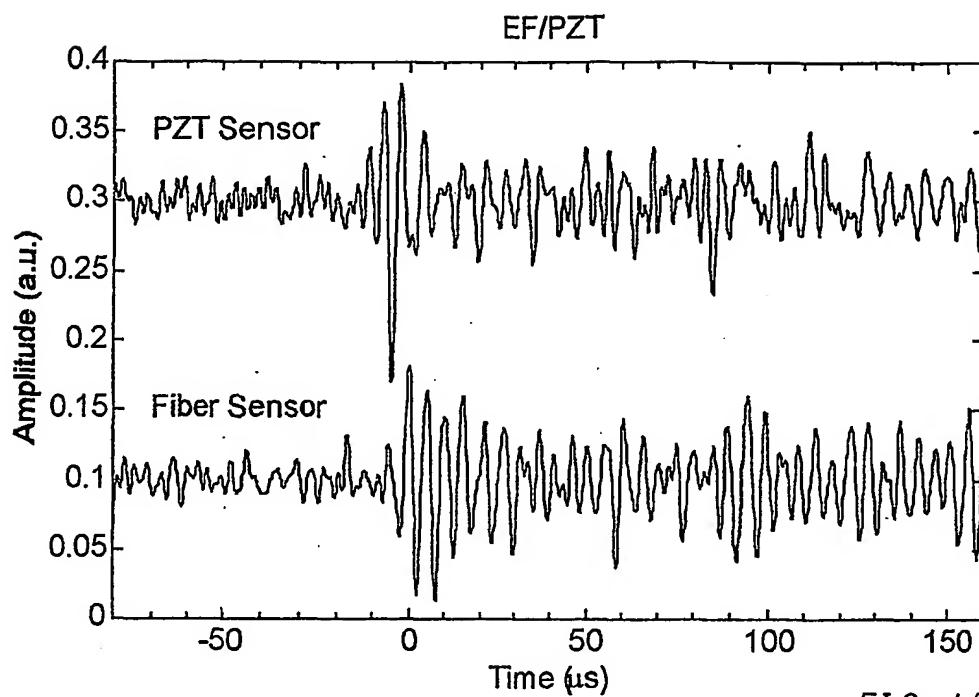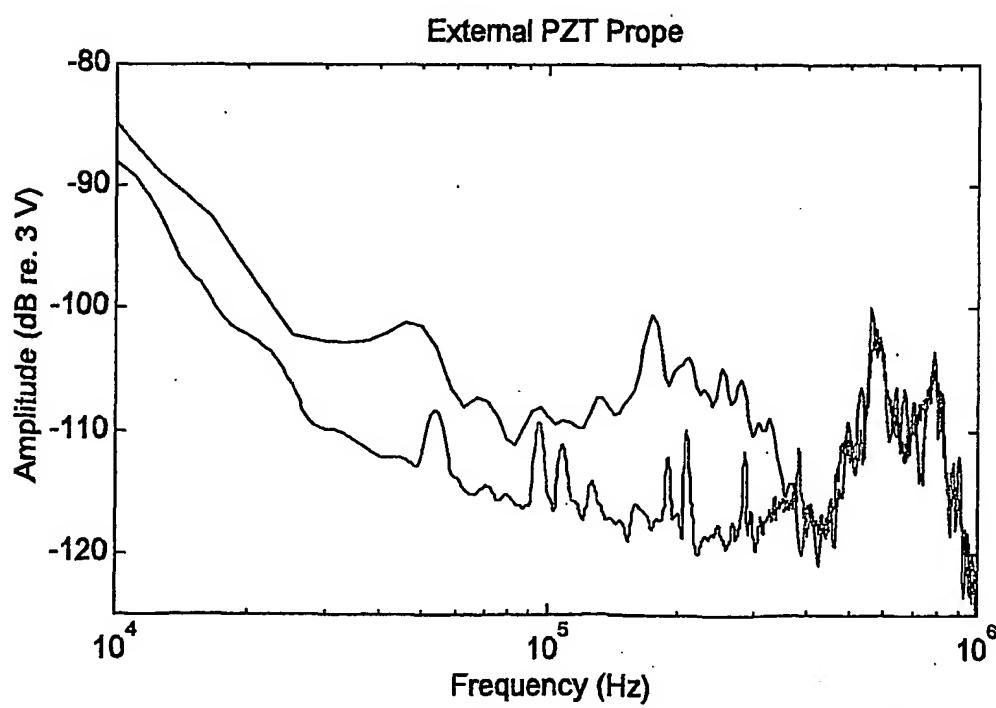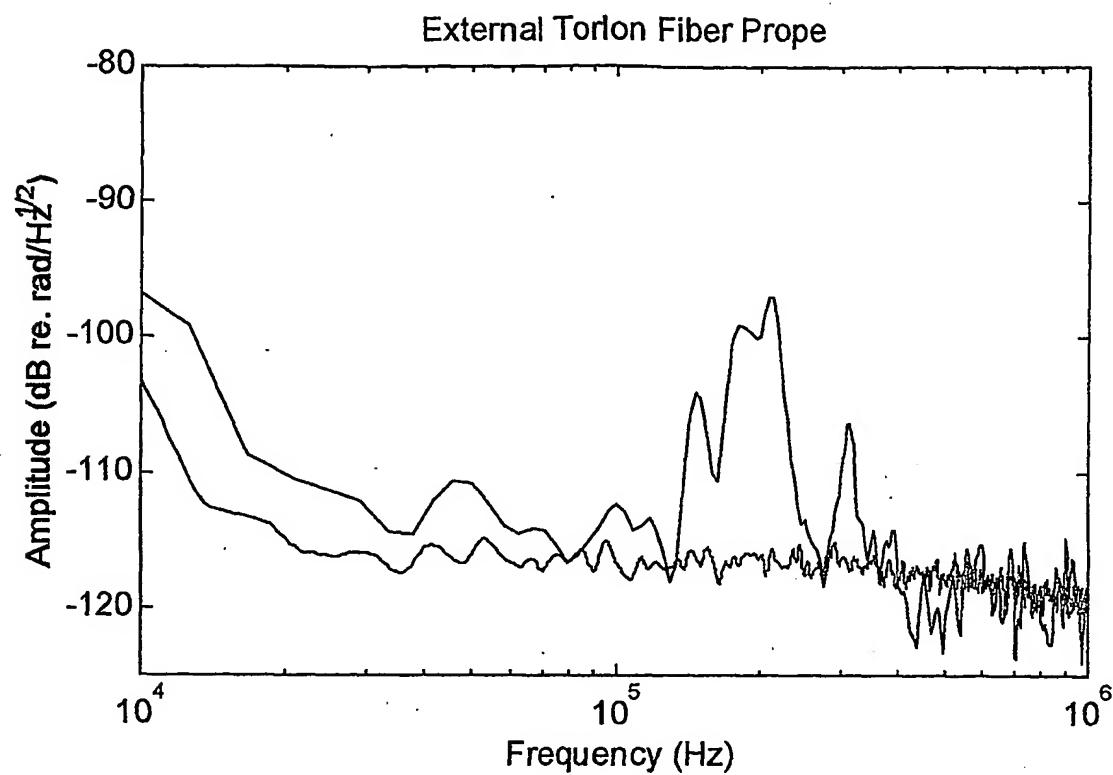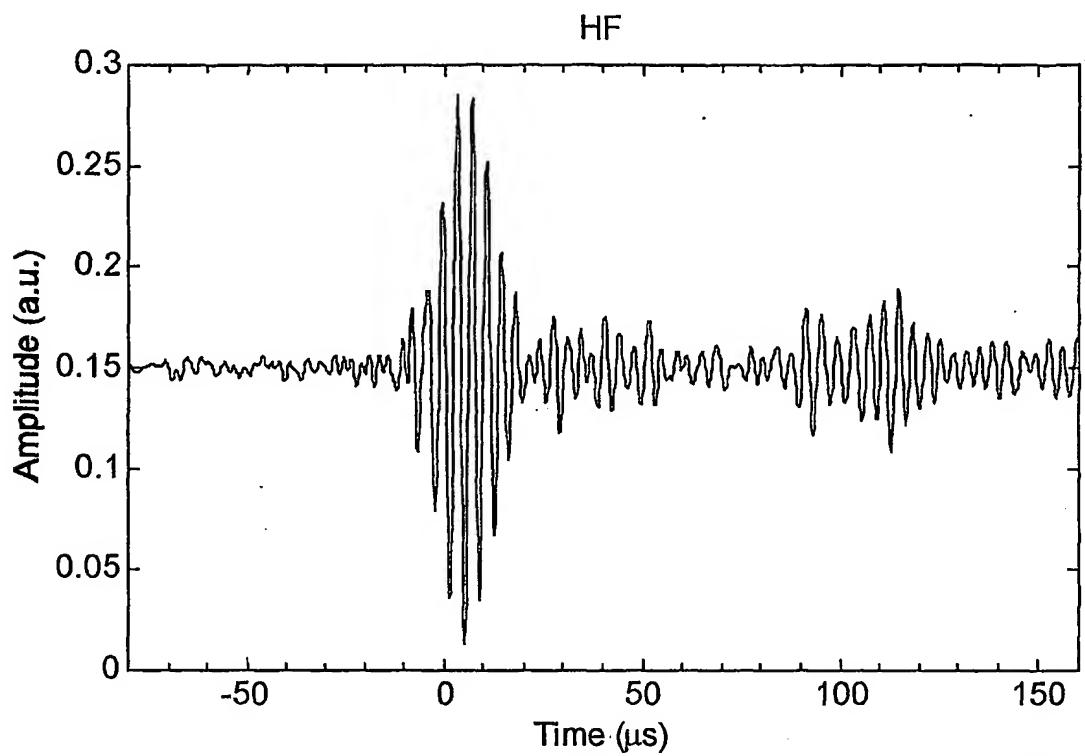
D = 7.4mm

80mm

130mm

FI G. 1B

D = 12mm

L = 100mm

t

Δ

FI G. 1C

D = 15mm

t

Δ

11 12 24 23 22 22 21

FIG. 2A

37 35 36 35 34 33 2 13

FIG. 2B

45   2   14   43   41

FIG. 2C

51 52 3 12

55

53 54

57 58

FI G. 3A

55 2

51 54

53

FI G. 3B

55 3 56

51 2

53

FI G. 3C

FIG. 4A

FIG. 4B

External Torlon Fiber Prope

FI6. 4C

HF

FIG. 5A

HF Prope

FIG. 5B

Laser

FIG. 6A.

Laser
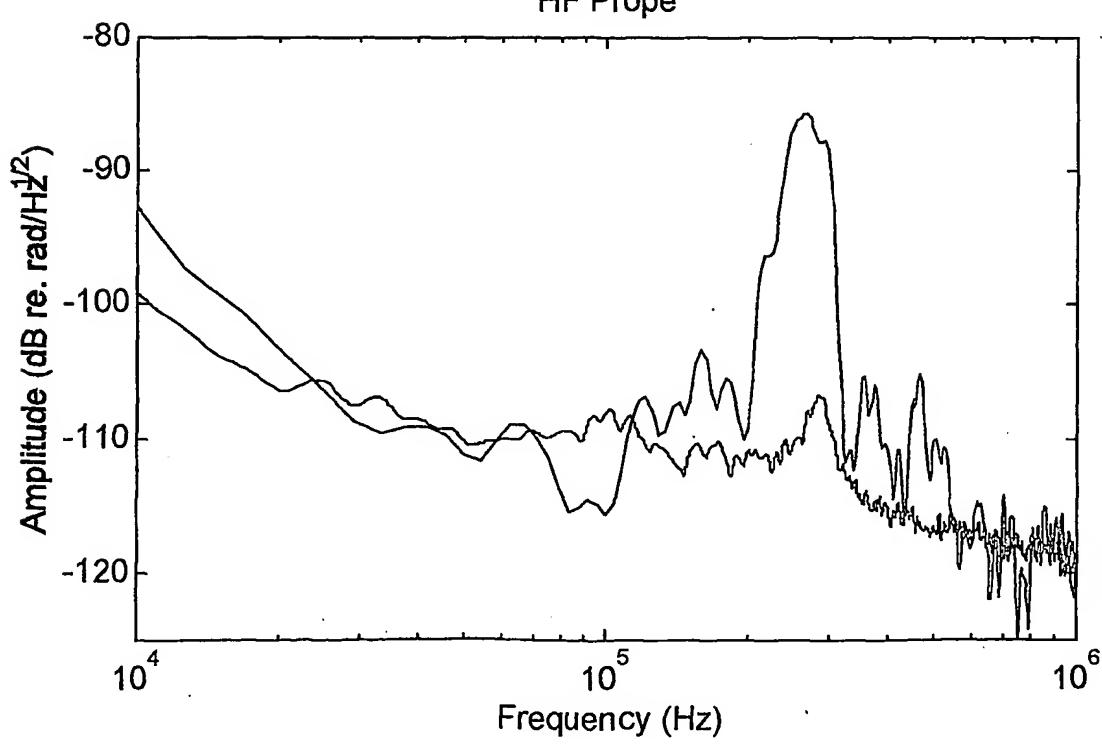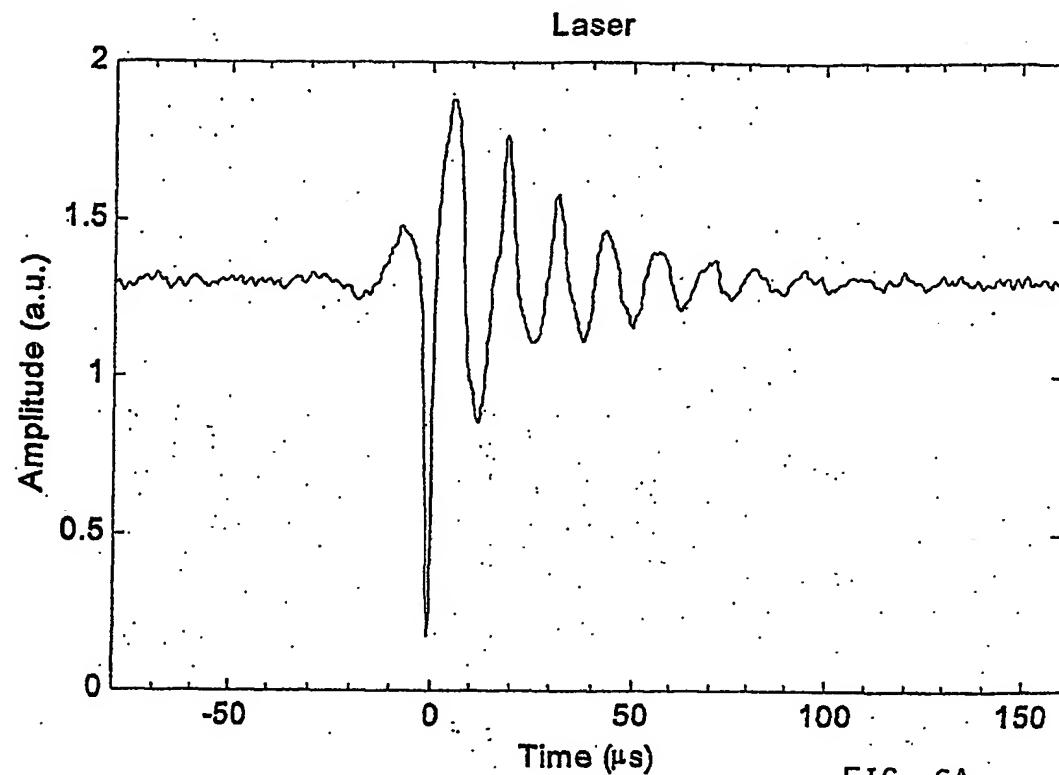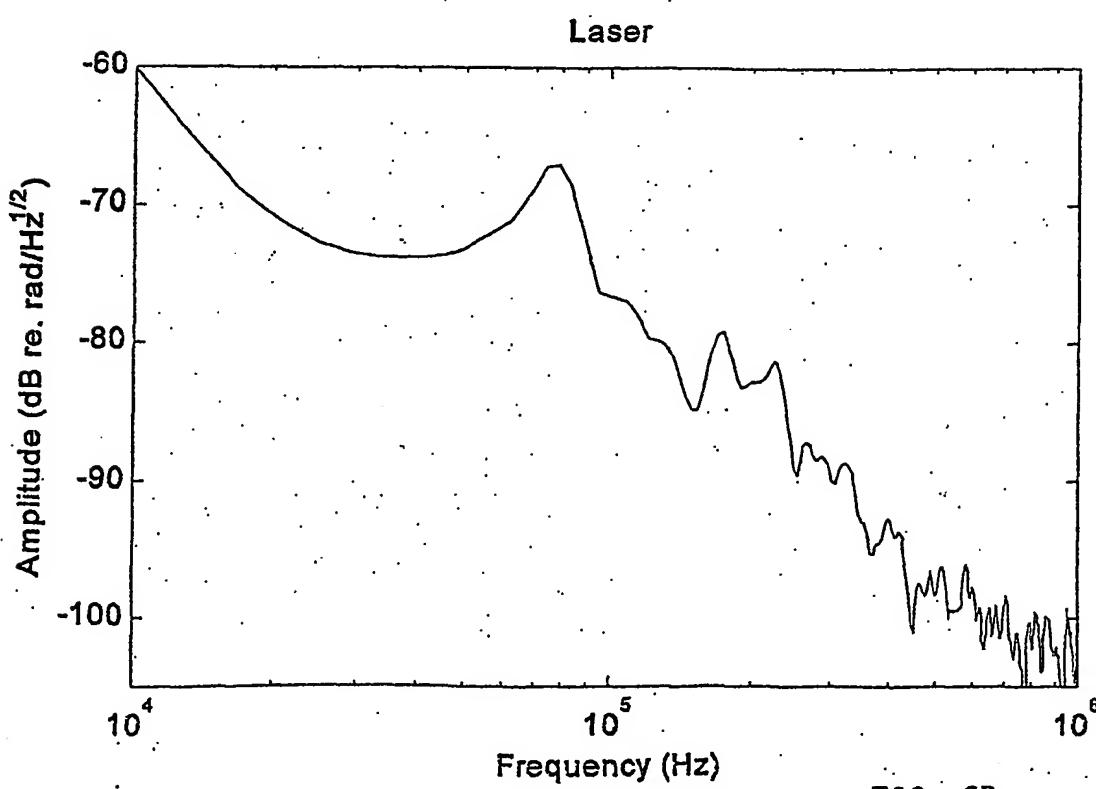
FIG. 6B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G01N 21/85, G01N 15/02, G01H 9/00
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G01N, G01H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5767411 A (MARON, R.J.), 16 June 1998 (16.06.98), column 2, line 44 - line 49; column 3, line 36 - line 39	1-10
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Y	FR 2490912 A1 (COMPAGNIE GENERALE D'ELECTRICITE, SOCIETE ANONYME), 26 March 1982 (26.03.82), abstract	1-10
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Y	US 5245290 A (CANNON, D.W. ET AL), 14 Sept 1993 (14.09.93), abstract	1-10
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A	US 5625724 A (FREDERICK, D.A. ET AL), 29 April 1997 (29.04.97)	1-10
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[X] Further documents are listed in the continuation of Box C.   [X] See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 January 2002	2 6 -01- 2002
Name and mailing address of the ISA/	Authorized officer
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Form PCT/ISA/210 (second sheet) (July 1998)

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SU 1638580 A ((FEPO) FAR E POLY) 1991-03-30 (abstract) World Patents Index [on line]. London, U.K.: Derwent publications, Ltd. [retrieved on 2002-01-22]. Retrieved from: EPO WPI Database. DW199209, Accession No. 1992-071419 --	1-10
A	US 5844927 A (KRINGLEBOTN, J.T), 1 December 1998 (01.12.98) -- --------	1-10

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				JP	3034816	B	17/04/00
				JP	10030955	A	03/02/98
				NO	971036	A	08/09/97
US	5844927	A	01/12/98	GB	2299203	A,B	25/09/96
				GB	9605822	D	00/00/00
				NO	302441	B	02/03/98
				NO	951052	A	23/09/96